CALC-SILICATE ROCKS AT TOOLANGI, VICTORIA

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ABSTRACT: Calc-silicate rocks outcrop over a small area on Blue Mount, near Toolangi, Victoria. They were originally a sequence of calcareous mudstones and argillaceous limestones of Late Silurian-Early Devonian age, which were contact metamorphosed by a series of small granodiorite intrusions in the Late Devonian. The rocks are mainly fine-grained, pale grey hornfels with localized development of grossular-rich spheroids, aggregates and spots. Some specimens show different alteration textures, where originally dark hornfelses have been altered by reaction with metamorphic fluids.

Minerals present include grossular, diopside, wollastonite, prehnite, vesuvianite, calcite, quartz, sphene, scolecite, K feldspar and plagioclase, nearly always as fine-grained aggregates. Only wollastonite and grossular develop as crystals which are visible to the naked eye.

The bulk chemistry of the rocks is variable and original compositions have been modified during metamorphism. Analyses of coexisting dark (metamorphic) and pale (metasomatized) hornfels suggest that Ca, Si, Al, S, Cl and Na were the main mobile elements, with the alteration resulting in the removal of Si, Al, Na and S from the original hornfels and the concentration of Ca, K, Fe, Mg, Ba, Sr and Cl in the resulting pale hornfels.

The calc-silicate assemblage crystallised in a metamorphic-metasomatic event in which initial prograde contact metamorphism, which may have been largely isochemical, was overlapped by metasomatism which led to the partial homogenization of the metasedimentary sequence and localized development of coarser skarn-like textures. Solutions responsible for the metasomatism were probably derived mainly from the sedimentary sequence or from meteoric sources. The lack of iron-enrichment suggests that the influence of magmatic fluids was minimal.

Comparison of the various assemblages observed in the Blue Mount rocks with those in calculated and experimentally determined equilibria suggests that the maximum temperature of the prograde metamorphism was between 500° and 550°, at pressures, estimated stratigraphically, of the order of 0.5 Kb or less. The solutions at, and following, the metamorphic peak were water-rich ($X_{CO_2} < 0.2$). Retrogression was marked by localized crystallisation of vesuvianite, prehnite and scolecite.

Calc-silicate rocks from contact metamorphic aureoles are rare in Central Victoria, reflecting the scarcity of calcareous sediments in sequences intruded by Palaeozoic granitic rocks. Small scale occurrences have been reported from the aureoles of the Bulla Granite (Tattam 1925) and the Strathbogie Batholith near Bonnie Doon (Phillips & Wall 1980). Hornfels containing calc-silicate assemblages were recorded in the Maldon goldfield (Moon 1897), while Lindner (1953) described vesuvianite and brucite from the contact of a gabbroic intrusion into the Ordovician Digger Island Limestone at Waratah Bay (recent evidence suggests this latter contact is an unconformity—Singleton pers. comm. 1984, Birch unpub. data).

Probably the most extensive suite of calc-silicate rocks occurs on Blue Mount, about 3 km south of Toolangi (Fig. 1). Kenley (1958) briefly described the geology of the area in preparation for the construction of the seismic observatory on the Mount and subsequently drafted a map of the observatory excavation. However, no additional petrological or mineralogical studies of the unusual rock-types exposed were carried out until specimens were collected for the National Musuem of Victoria in 1978/9.

GEOLOGY

Interbedded Late Silurian to Early Devonian siltstones and sandstones of the Dargile and Humevale Formations (VandenBerg 1971) form the bedrock of the area (Fig. 1). The sediments are folded with a roughly north-south axial trend. Three kilometres to the east of Blue Mount (elevation 604 m) the north-south trending Yellingbo Fault Zone brings the acid-intermediate volcanic rocks of the Acheron Cauldron Complex into contact with the basement (Dudley et al. 1971). Intrusion of granitic rocks associated with the complex (the Black Range composite intrusion) has resulted in a belt of contact metamorphism from 1 to 4 km wide in the basement sediments. Between Toolangi and Healesville, four small outcrops of granodiorite occur in a line approximating regional trends (Fig. 1). These probably represent apophyses of a larger near-surface intrusion responsible for the contact metamorphic effects.

On Blue Mount, the contact metamorphic rocks consist mainly of light grey calc-silicate hornfels. Several decomposed feldspathic dykes were mapped in the original excavation for the observatory (Kenley 1958). The full extent of the calc-silicate rocks was not determined but the outcrop appears to be restricted to Blue Mount, and probably would not exceed 1 km² in outcrop area.

PETROGRAPHY

The light grey hornfels is cherty, sometimes porcellainous, in appearance. Internal casts of shelly fossils are occasionally found. Much of the pale hornfels contains thin bands or irregular patches of a dark grey, similarly fine-grained rock. Many of the macroscopic

replacement-type textures (Figs 2, 3) suggest that the pale-coloured hornfels has resulted from alteration of the dark rock type. What appears to be original bedding is preserved locally (Fig. 4) in the form of alternating dark and light bands. In general, the pale and dark grey hornfels are too fine-grained to enable individual minerals to be distinguished in thin section. However, X-ray diffraction and electron microprobe investigations reveal that K feldspar, diopside and quartz are the dominant minerals in both rock types, with minor calcic plagioclase, grossular, wollastonite, calcite, sphene, apatite and opaques. There is little textural or mineralogical distinction between dark and light coloured rock types in thin section. However, the dark hornfels has more finely disseminated opaque grains, mainly sulphides, while the pale hornfels is more turbid in appearance.

The most noticeable features of the more massive, pale coloured hornfels are dark grey spots and clots, which are locally abundant. These range from simple circular or oval shapes up to 2 cm across, occurring either singly or as beaded groups (Fig. 5) to larger coarse-grained patches 10 to 12 cm wide. The margins of these blebs and patches are always curved and generally distinct, but in some varieties, more diffuse margins give the rock an overall mottled appearance. Often the clots resemble spherules, with distinct rim and core sections in hand specimen. On weathered surfaces, the clots stand out as small nodules. The main mineral forming the clots is grossular, with minor wollastonite, diopside and sphene. In clots with a distinct rim and core, the rims are richer in grossular (95%) than the core (80%).

Finely laminated rock types are occasionally developed. In these and in the mottled rock types, coarser patches, of the order of several mm across, and short veinlets, are often developed. These generally contain assemblages involving wollastonite, grossular, diopside, prehnite, calcite and quartz.

MINERALOGY

The mineralogy of the calc-silicate rocks is relatively restricted, reflecting the small size of the outcrop, the uniformity of formation conditions and, to an extent, the similarity of the original sedimentary components.

GROSSULAR: As the major constituent of the spherulitic-like clots, the grossular appears mid to dark grey, occasionally with brownish or pinkish overtones, translucent to opaque and with a greasy lustre. Where individual grains can be distinguished in thin section, the grossular is not isotropic, but shows low birefringence. In some of the coarser patches and in the mottled rock types, individual dodecahedral outlines can be distinguished, and the grossular exhibits strong twinning effects, similar to the sixling twinning observed in some occurrences of cordierite (Fig. 6). This strong similarity was probably responsible for the original description of the Blue

Fig. 1 — General geological and locality map of the Healesville-Toolangi area. The calc-silicate hornfels occurs on and in the vicinity of Blue Mount.
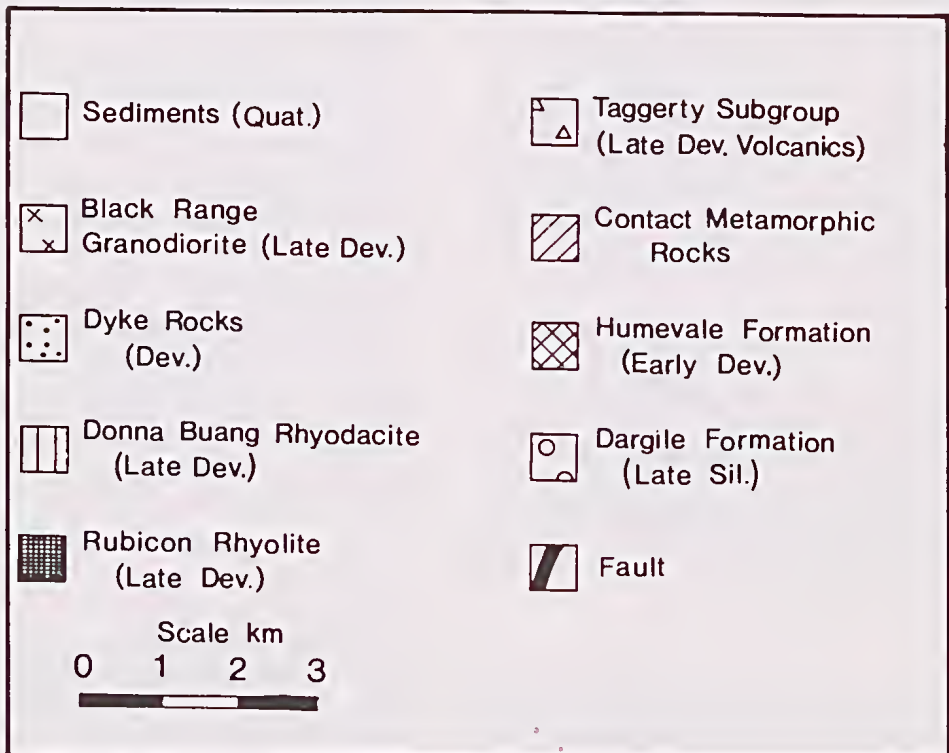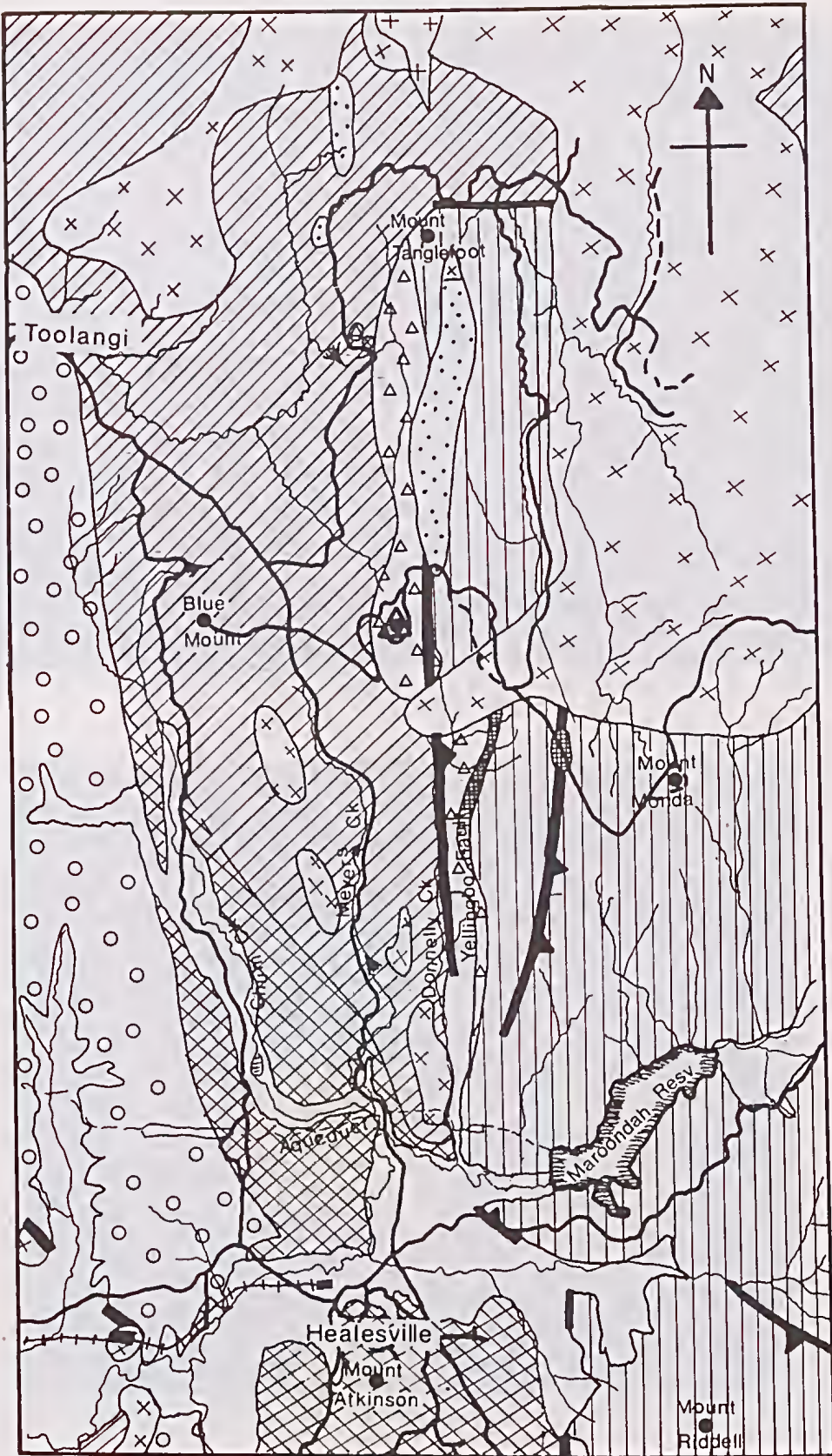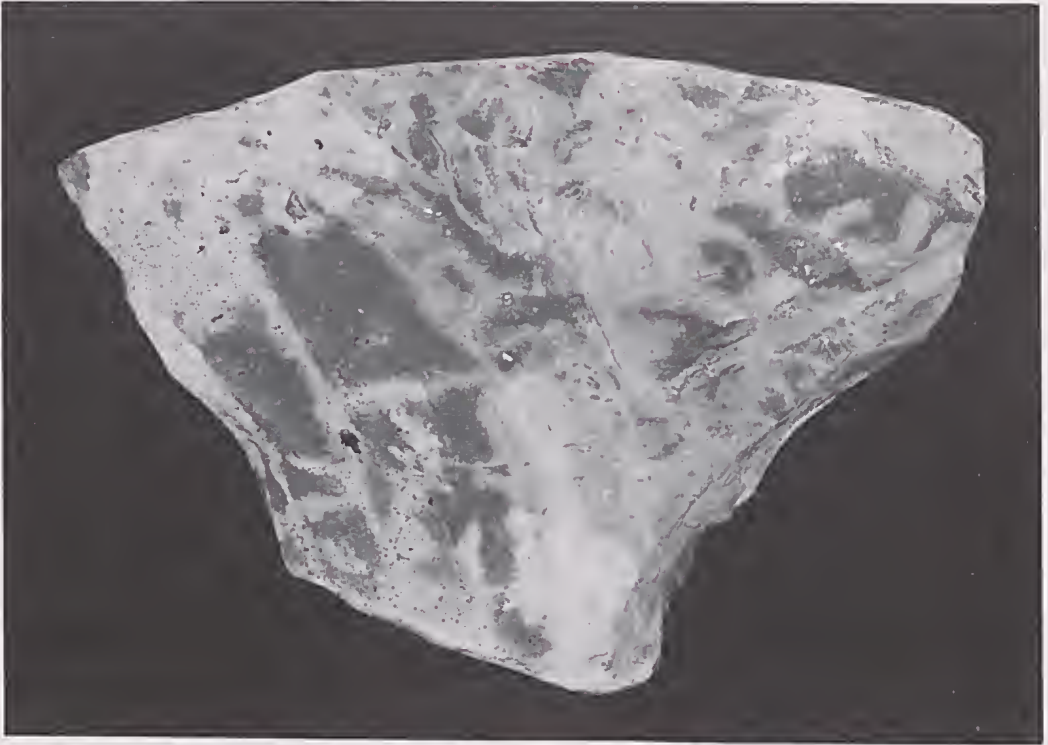
Fig. 2 — Replacement texture in calc-silicate hornfels. Alteration of originally dark hornfels has proceeded via a network of fractures (NMV specimen E10549A, 8.0 cm long).
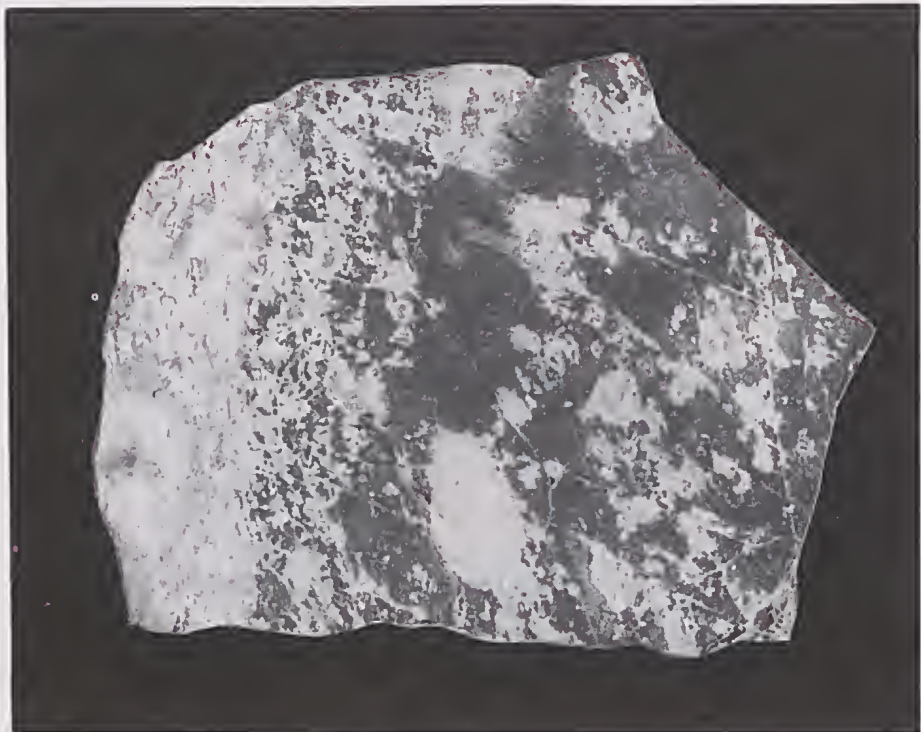

Fig. 3 — Pervasive alteration texture in calc-silicate hornfels (NMV specimen E10549C, 5.5 cm long).

Fig. 4—Specimen showing remnant layers (original bedding, subsequently faulted) of unaltered dark hornfels in pale alteration product. Specimen is 8.5 cm across.
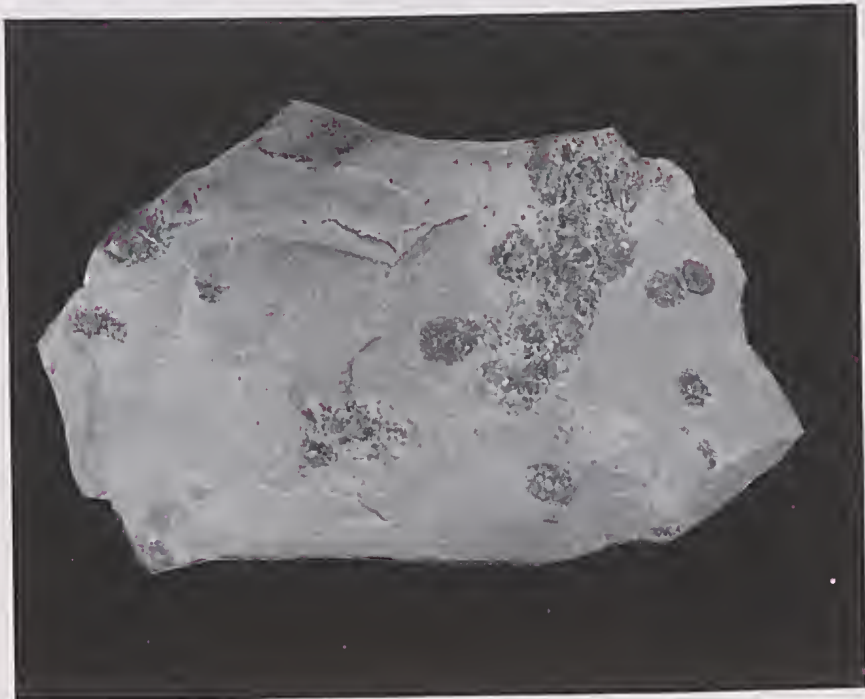

Fig. 5—Grossular blebs in pale hornfels. The largest clot is 0.5 cm across (NMV specimen E10280).

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Fig. 6 — Photomicrograph showing large non-isotropic grossular crystal (1 mm across) in fine-grained calc-silicate hornfels (calcite, diopside, quartz) (NMV specimen E10283).

Mount hornfels as showing local development of cordierite blebs (Kenley 1958). Anisotropism and twinning in garnets of the grossularite group is well documented (Deer *et al.* 1962). Light grey translucent grossular crystals up to 5 mm across are occasionally found lining cavities on weathered outcrop surfaces. Microprobe analysis shows the grossular to be quite uniform in composition. Pyrope and spessartite components are minimal and andradite is the main substitutional end member (Table 1). However, overall iron contents are low (Gr:Ad > 85:15) and are characteristic of garnet compositions in contact metamorphic rocks rather than skarns produced by magmatically-derived fluids (Einardi & Burt 1982).

WOLLASTONITE: Wollastonite is disseminated through much of the pale hornfels and is a minor constituent of the grossular spherules. When visible under the microscope, in some of the coarse-textured rocks, and in patches and veinlets in fine-grained rocks, it forms fibrous aggregates usually associated with grossular and diopside (Fig. 7). Patches of white, coarsely-crystalline fibrous wollastonite, up to 6 cm across, with individual crystals up to 2 cm long, may occur in the pale grey hornfels (Fig. 8). Microprobe analyses reveal only small amounts of Fe and Mn (Table 1).

DIOPSIDE: Diopside is present in all rock types, as clouds of tiny, euhedral, equidimensional crystals included in most of the other minerals. Larger diopside crystals occur in patches of grossular and wollastonite in the coarser-textured rocks. Thin veinlets consisting of diopside and quartz occur surrounded by narrow bleached zones in some of the hornfels (Fig. 9). Microprobe

TABLE 1

ELECTRON MICROPROBE ANALYSES OF GROSSULAR AND WOLLASTONITE IN THE BLUE MOUNT CALC-SILICATE ROCKS.

Wt%	1	2	3
SiO_2	38.64	38.85	52.21
TiO_2	0.80	0.36	0.12
Al_2O_3	20.99	18.48	0.08
Fe_2O_3	2.30	6.88	—
FeO	—	—	0.43
MnO	0.14	0.04	0.09
MgO	0.03	0.02	—
CaO	37.50	36.59	47.68
Na_2O	—	0.05	—
K_2O	—	—	—
BaO	0.08	0.14	—
Total	100.48	101.41	100.61
	Structural Formulae		
	(16 cats, 24 'O')		(4 cats, 6 'O')
Si	5.848	5.899	2.004
Ti	0.091	0.041	0.003
Al	3.745	3.308	0.004
Fe^{3+}	0.262	0.786	—
Fe^{2+}	—	—	0.014
Mn	0.018	0.005	0.003
Mg	0.007	0.005	—
Ca	6.082	5.953	1.961
Na	—	—	—
K	—	—	—
Ba	0.005	0.008	—

1, Grossular (E10283); 2, Grossular (E10280); 3, Wollastonite (E10280).
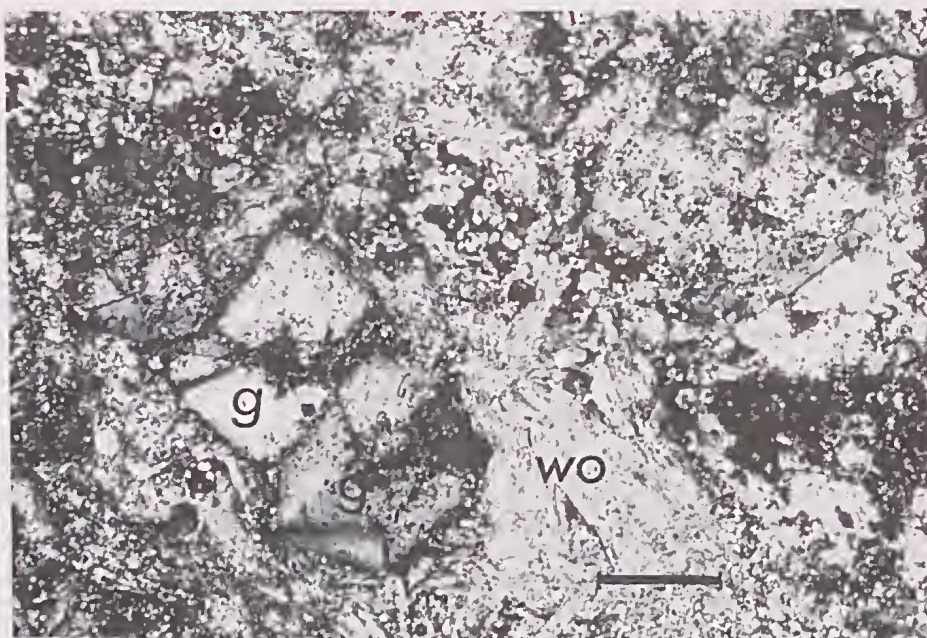
Fig. 7—Fibrous wollastonite (wo) associated with grossular (g) and small diopside crystals (NMV specimen E10282). Scale bar = 0.5 mm.
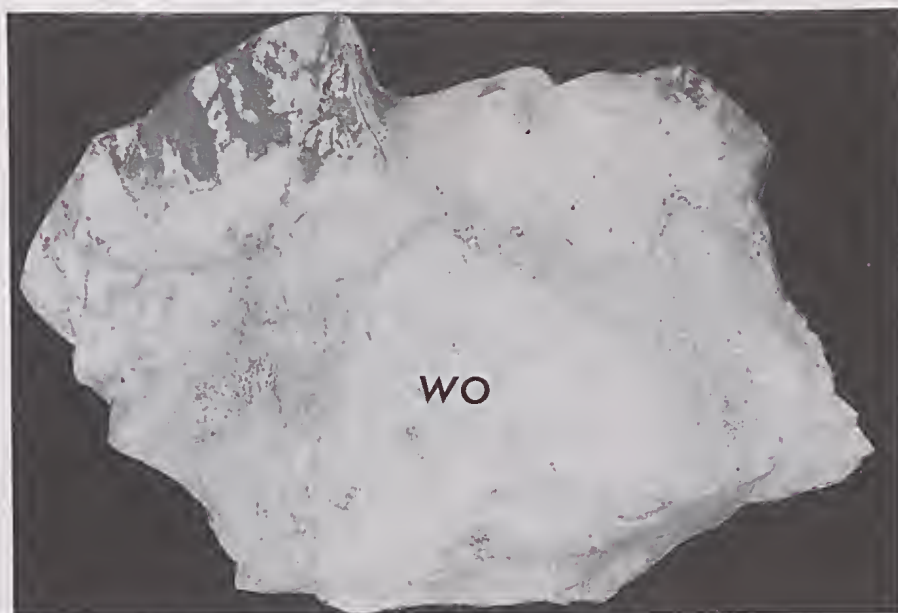

Fig. 8—Patch of coarse wollastonite 4.5 cm across in fine-grained calc-silicate hornfels (NMV specimen M34812).

TABLE 2

ELECTRON MICROPROBE ANALYSES OF DIOPSIDE AND SPHENE IN
THE BLUE MOUNT CALC-SILICATE ROCKS.

Wt%	1	2	3
SiO_2	51.96	51.89	30.99
TiO_2	0.08	0.10	36.90
Al_2O_3	0.13	0.44	3.09
Fe_2O_3	0.87	–	–
FeO	11.51	15.34	0.13
MnO	0.73	0.20	–
MgO	9.86	8.00	0.05
CaO	24.86	24.24	28.35
Na_2O	0.10	0.11	–
Cr_2O_3	0.07	0.11	–
H_2O calc.	–	–	1.18
Total	100.17	100.43	100.69

	Structural Formulae		
	(4 cations, 6 oxygens)		(12 cats, 20 'O', 1[OH,F])
Si_{iv}	1.985	1.998	3.937
Al_{vi}	0.006	0.002	0.063
Al	–	0.018	0.400
Ti	0.002	0.003	3.525
Fe^{3+}	0.025	–	–
Fe^{2+}	0.368	0.494	0.014
Mn	0.024	0.007	–
Mg	0.562	0.459	0.009
Ca	1.018	1.000	3.859
Na	0.007	0.008	
Cr	0.002	0.003	
OH	–	–	1.000

1, Diopside in quartz-diopside veinlet (E10547); 2, Diopside crystal (E10282); 3, Sphene crystal (E10281).

analysis reveals a relatively narrow compositional range, with $Mg/(Fe+Mg)$ varying between 0.66 and 0.48 (Table 2).

K FELDSPAR: K feldspar is the main mineral in many of the pale grey porcellainous rock types. However, due to its variable abundance and extremely small grain size (<0.05 mm) precluding optical detection, X-ray powder diffraction is the simplest method of determining both its relative abundance and composition. The latter can only be determined where quartz is virtually absent, as the $\bar{2}01$ reflection for K feldspar is overlapped by the proportionally much stronger 101 reflection for quartz. K feldspar compositions in specimens of the pale-grey hornfels were estimated to range from $Or_{85}Ab_{15}$-$Or_{92}Ab_8$, using the $\bar{2}01$ method of Wright (1968). Microprobe analysis was limited by the small grain size, but analyses confirmed the composition estimated from the X-ray diffraction data. Small amounts of both Ba and Ca were detected (Table 3). Attempts to determine K feldspar compositions by X-ray diffraction in coexisting pale and dark regions were hampered by an abundance of quartz in either one or both portions. Microprobe analyses however indicate that alkali feldspars in the dark fraction are variable in composition, and are less potassic and more calcic than those in the pale regions (Table 3).

The structural states of feldspars were determined using the three-peak method of Wright (1968). The 060 and $\bar{2}04$ reflections for K feldspar are not obscured by quartz peaks and their positions were measured whenever K feldspar was sufficiently abundant. Using a quantifying method developed by Ragland (1970), K feldspars in the pale rock types were shown to have structural states very close to that of orthoclase, but
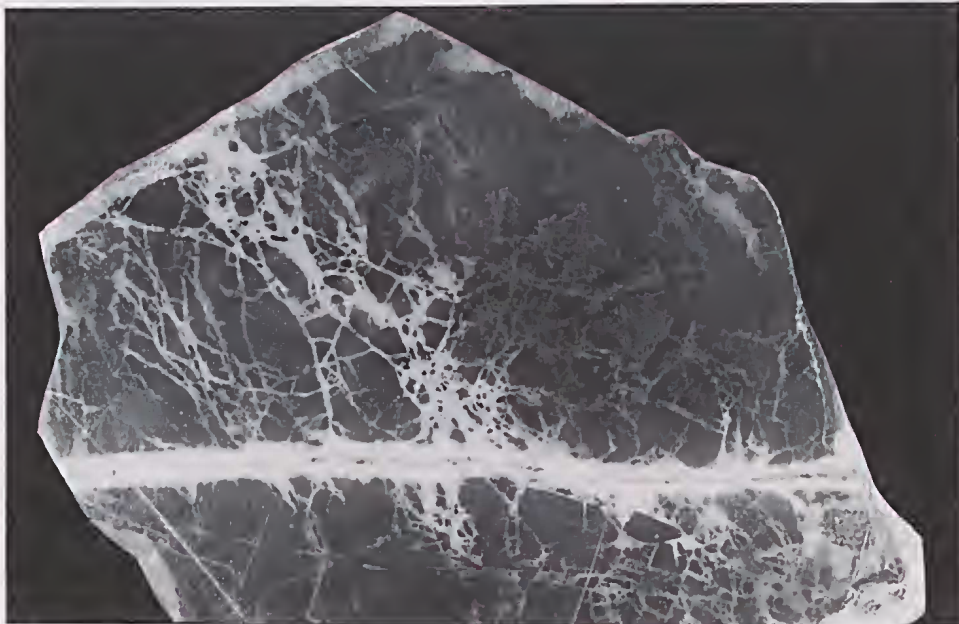

Fig. 9—Thin diopside-quartz veinlet surrounded by an alteration zone 2.5 mm wide, in dark hornfels (NMV specimen E10547).

TABLE 3

ELECTRON MICROPROBE ANALYSES OF FELDSPARS IN THE BLUE MOUNT CALC-SILICATE ROCKS

Wt%	1	2	3	4	5
SiO_2	65.32	64.36	64.96	64.59	57.00
Al_2O_3	18.93	19.14	19.94	19.60	24.31
Fe_2O_3	0.08	0.29	0.24	0.19	0.46
MgO	—	—	0.05	0.07	—
CaO	—	0.06	1.76	3.23	10.76
Na_2O	0.94	0.62	6.27	3.19	2.95
K_2O	14.64	14.87	5.65	8.80	2.38
BaO	0.96	0.70	0.26	0.24	0.25
Total	100.87	100.04	99.13	99.91	98.11
Endmember Compositions (mol.%)					
Or	89.5	92.5	33.8	53.6	14.9
Ab	8.7	5.9	56.9	29.5	28.1
An	—	0.3	8.8	16.5	56.5
Cel	1.8	1.3	0.5	0.4	0.5

1, K feldspar in pale, finegrained rock (E10280); 2, K feldspar in pale fraction (E10544); 3, Alkali feldspar in dark fraction (E10544); 4, Alkali feldspar in dark fraction (E10544); 5, Plagioclase in dark fraction (E10547).

with between 5-10% of ordering towards maximum microcline. K feldspars in the dark fraction were always slightly more ordered, with about 20-25% ordering towards maximum microcline. These data are shown in Table 4 and Fig. 10. It can therefore be concluded that the process which partially or completely altered the dark hornfels, has resulted in the development of a more disordered, more potassic feldspar in the pale alteration zones.

PLAGIOCLASE: X-ray diffraction revealed that plagioclase is present in most of the fine-grained rock types, but as a minor mineral only. Microprobe analyses suggest it is mainly labradorite (Table 3).

QUARTZ: The abundance of quartz varies, reaching a maximum in some of the dark hornfels. It is absent from the spherule-bearing porcellainous variety. In the fine-

TABLE 4

K FELDSPAR STRUCTURAL STATE EXPRESSED AS PERCENTAGE ORDERING TOWARDS MAXIMUM MICROCLINE FROM ORTHOCLASE

Sample	Dark	Light	Comp. (est.)
E10713	—	9	—
E10280	—	6	$Or_{88}Ab_{12}$
E10547	21	—	—
E10549C	24	6	$Or_{94}Ab_6$(light)
E10549B	20	7	$Or_{95}Ab_5$(light)
E10544	20	11	$Or_{95}Ab_5$(light)
E10549A	42	27	—

NOTES ON METHOD: Two smear mounts of each sample were run in duplicate using Ni-filtered CuK_α radiation, with a chart speed of 2 cm/minute and a scanning rate of 0.25°/minute. $KBrO_3$ was used as an internal standard for the three peak positions measured.

grained hornfels it forms small anhedral grains, possibly representing original recrystallized detrital fragments. Patches of interstitial quartz are associated with larger grains of grossular, wollastonite, diopside, vesuvianite, prehnite and calcite in the coarser-textured rocks. Small quartz-diopside veinlets are evidence for mobilization of Si during metamorphism (Fig. 9).

CALCITE: Calcite is most prominent in the coarser-textured rocks, where it forms interstitial patches. It generally encloses small diopside inclusions and may coexist with nearly all other minerals, including quartz. It is absent or a minor phase only in many of the fine-grained hornfels.

VESUVIANITE: Vesuvianite occurs in several rock types, forming either blocky crystals resembling phenocrysts or pale brown zoned prismatic crystals (Fig. 11). In both cases, the maximum crystal length is about 1.5 mm. Microprobe analyses (Table 5) on the blocky crystals and the cores of the pale brown prisms are similar. Fe/Mg ratios are variable and the vesuvianite contains about 1.4% TiO_2 and between 1 and 2% F. The rims of the prismatic crystals have an unusual composition (Table 5) with more structural water, and do not recalculate to a vesuvianite structural formula. The identity of this phase is unknown.

PREHNITE: Prehnite is widespread in coarser-grained rock types as irregular grains showing bright interference colours. It appears to be an interstitial, late-crystallizing mineral. A typical microprobe analysis is shown in Table 6.

SPHENE: Small crystals of sphene occur in the rims of the grossular blebs, in the matrix of the fine-grained hornfels and in the coarser-textured rock types. The very small crystal size (about 0.03 mm) makes the determina-
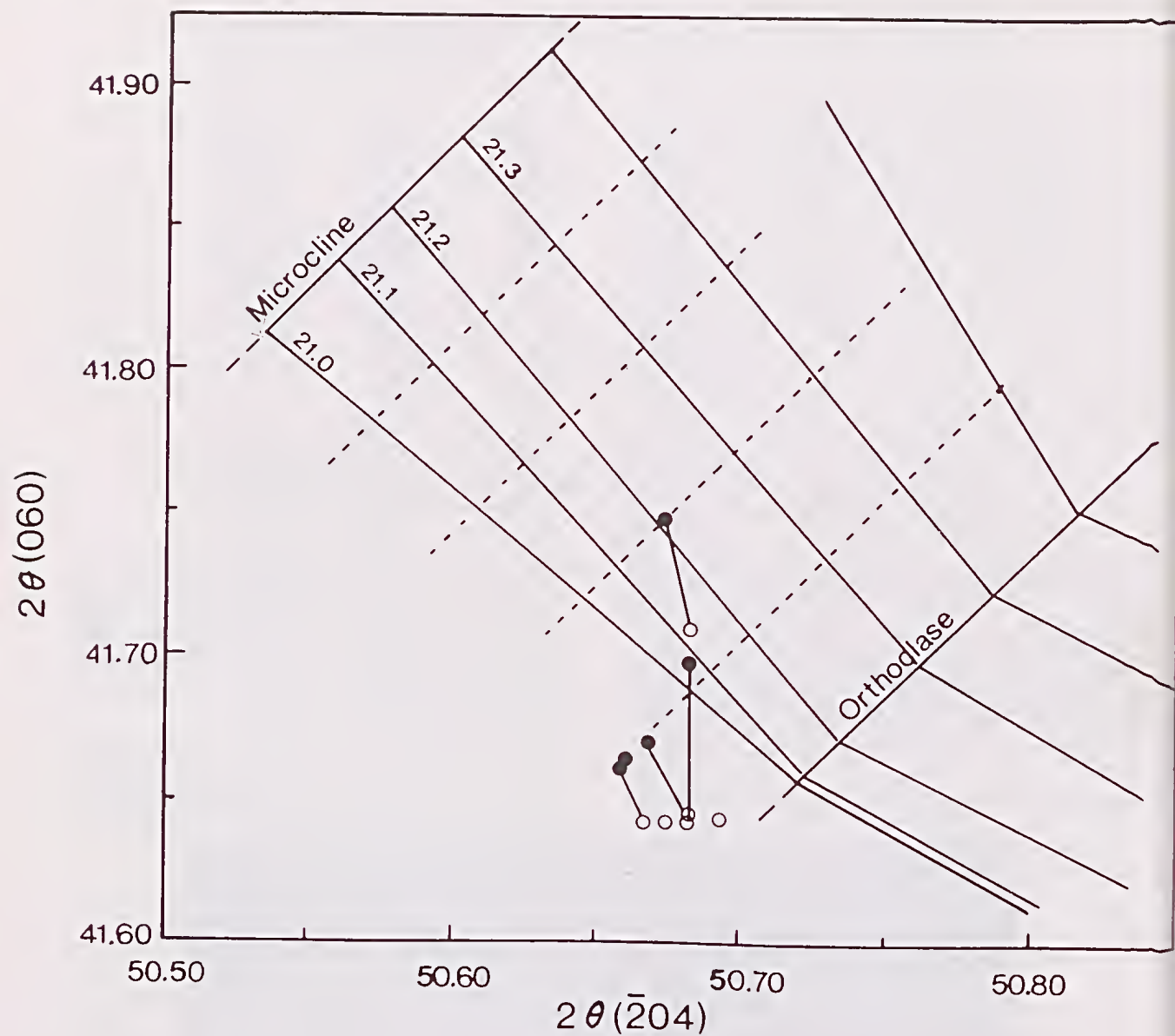
Fig. 10—$2\theta_{\bar{2}04} - 2\theta_{060}$ plot for K feldspars in specimens of the fine-grained calc-silicate rocks (see also Table 4 and text for discussion). Feldspars coexisting in dark (full circles) and pale hornfels (open circles) are joined by tie-lines.

Table 5
Electron Microprobe Analyses of Vesuvianite in the Blue Mount Calc-silicate Rocks

Wt%	1	2	3
SiO$_2$	35.90	35.58	38.57
TiO$_2$	1.55	1.40	1.81
Al$_2$O$_3$	15.19	16.23	14.09
FeO	3.51	4.14	2.94
MnO	—	0.06	0.10
MgO	2.61	1.33	0.72
CaO	35.80	36.07	25.38
Na$_2$O	0.04	0.09	0.05
BaO	—	—	0.79
F	0.82	1.08	0.16
Cl	—	0.61	0.16
*H$_2$O	2.05	1.77	0.10
−0=F,Cl	0.34	0.59	0.10
Total	97.13	97.77	84.87

Structural Formulae
(25 cations, 38 oxygens, 4 OH)

Si	8.840	8.763	—
Al	4.409	4.710	—
Ti	0.287	0.259	—
Fe^2.	0.722	0.853	—
Mn	—	0.012	—
Mg	0.958	0.487	—
Ca	9.444	9.517	—
Na	0.018	0.045	—
Ba	—	—	—
F	0.637	0.841	—
Cl	—	0.254	—
OH	3.363	2.905	—

1, Vesuvianite crystal (E10545); 2, Core of pale brown crystal (E10282); 3, Unknown phase rimming 2.
* Calculated

tion of physical properties difficult. A microprobe analysis is shown in Table 2.

SCOLECITE: This calcium-rich zeolite is rare, with only two small crystals detected by microprobe (Table 6).

OTHER MINERALS: Very rare grains of yttrium phosphate were encountered during microprobe work. They are probably xenotime and may be detrital in origin. Several minute grains of chromite may have a similar origin. Pyrrhotite and arsenopyrite are the most abundant of the opaque minerals present, occasionally forming patches up to 2 mm across, but usually microscopic. Galena and sphalerite have been observed as small blebs up to 2 mm across and galena occasionally forms ragged grains in the core of spots.

MINERAL EQUILIBRIA
DARK HORNFELS WITH PALE ALTERATION: X-ray diffraction patterns were used to determine the mineralogy of five samples of fine-grained hornfels in which dark and pale fractions coexisted. The results are summarized in

Table 7. In three samples (E10544, E10549B & C) the quartz content in the initial assemblage (quartz, diopside, K feldspar, plagioclase, minor grossular) was reduced by the alteration. The only sample containing detectable calcite (E10549A) appeared largely unaffected.

There is no evidence remaining for the reactions producing K feldspar and diopside in the dark hornfels, as the reactants were consumed during prograde metamorphism. However, the most commonly observed reactions in siliceous carbonate rocks containing small amounts of Mg and Fe (defined approximately by the system CaO-MgO-SiO$_2$-H$_2$O-CO$_2$, e.g. Kerrick 1974) are:

1. dolomite + quartz→diopside + 2 CO$_2$ (Rice 1977)
2. tremolite + 3 calcite + 2 quartz→5 diopside + 3CO$_2$ + H$_2$O
3. muscovite + 6 quartz + 2K$^+$→3 K feldspar + 2H$_2$O + 2H$^+$

In the dark hornfels, the formation of small amounts of grossular was probably controlled by the equilibrium:

4. 2 calcite + anorthite + quartz→grossular + 2CO$_2$ (Gordon & Greenwood 1971).

Table 6
Electron Microprobe Analyses of Prehnite and Scolecite in the Blue Mount Calc-Silicate Rocks

Wt%	1	2
SiO$_2$	44.36	59.64
TiO$_2$	0.03	—
Al$_2$O$_3$	23.67	17.23
FeO	0.23	0.07
CaO	26.84	8.77
Na$_2$O	0.06	0.46
K$_2$O	—	0.28
BaO	0.14	0.06
Total	95.33	86.51

Structural Formulae

	(22 'O')	(72 'O')
Si	6.110	26.855
Al	3.843	9.147
Ti	0.003	—
Fe	0.026	0.027
Ca	3.961	4.232
Na	0.008	0.400
K	—	0.162
Ba	0.007	0.011

1, Prehnite (NMV E10282); 2, Scolecite (NMV E10282).

The amount of grossular formed would be determined by the amount of calcite present initially, as this appears to have been the least abundant reactant in the hornfels. The most obvious change in the fine-grained hornfels, that of colour, is due primarily to the oxidation of sulphides, and possibly carbonaceous matter.
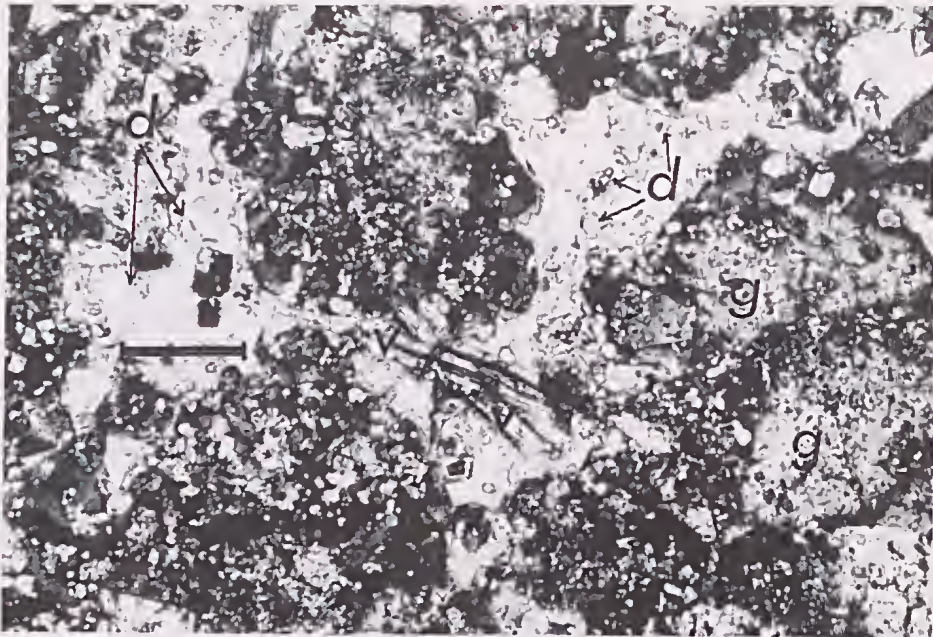
Fig. 11 — Prismatic vesuvianite crystals (v) in calcite patches associated with grossular (g) and diopside (d) (NMV specimen E10282). Scale bar = 0.5 mm.

COARSE-GRAINED ROCKS AND PATCHES: The mineralogy of coarse-textured rocks, and coarsely-crystallized patches in some of the fine-grained rocks, is relatively uniform. The following assemblages have been observed in thin section:

grossular + calcite + quartz + prehnite
grossular + wollastonite
diopside + sphene
wollastonite + quartz + calcite
vesuvianite + quartz + grossular
vesuvianite + calcite
calcite + prehnite + wollastonite + grossular + scolecite + sulphides

In some cases it is difficult to decide exactly what is an "assemblage" as textural relationships are not always clear. Thus, nearly all phases in the above assemblages contain clouds of minute diopside crystals, but these are considered to be early-formed and not necessarily part of any equilibria close to the peak of metamorphism. K feldspar and plagioclase (ss) coexist with these assemblages in the enclosing matrix.

As well as reaction 4, there are a number of other equilibria involving the observed phases and which may have been responsible for these assemblages. In approximate order of increasing temperature, these are:

5. vesuvianite + 4 quartz → 5 grossular + 3 diopside + wollastonite + $4H_2O$ (Hochella *et al.* 1982)
6. prehnite → anorthite + wollastonite + H_2O (Liou 1971)
7. calcite + quartz + rutile → sphene + CO_2 (Jacobs & Kerrick 1981)
8. calcite + quartz → wollastonite + CO_2 (Greenwood 1967)
9. grossular + quartz → 2 wollastonite + anorthite (Newton 1966)
10. calcite + anorthite + wollastonite → grossular + CO_2 (Gordon & Greenwood 1971)

TABLE 7
MINERALOGY OF FINE-GRAINED HORNFELS WITH DARK AND PALE FRACTIONS

Sample	Dark	Assemblages (main phases) Light	Main change
E10547	Q + Di + P + K	Q + Di + P + K(tr)	K reduced
E10549A	Cc + K + Di + P + Q + Gr(tr)	K + Cc + Di + P + Q + Gr(tr)	Largely unaffected
E10549B	Q + K + P + Di + Gr	K + Di + P + Q + Gr	Q reduced
E10549C	K + Di + P + Q + Gr	K + Di + P + Gr	Q removed
E10544	Q + K + Di + P + Gr(tr)	K + Di + Q + P + Gr(tr)	Q reduced

Q, Quartz; Di, Diopside; P, Plagioclase; K, K feldspar; Gr, Grossular; Cc, Calcite.
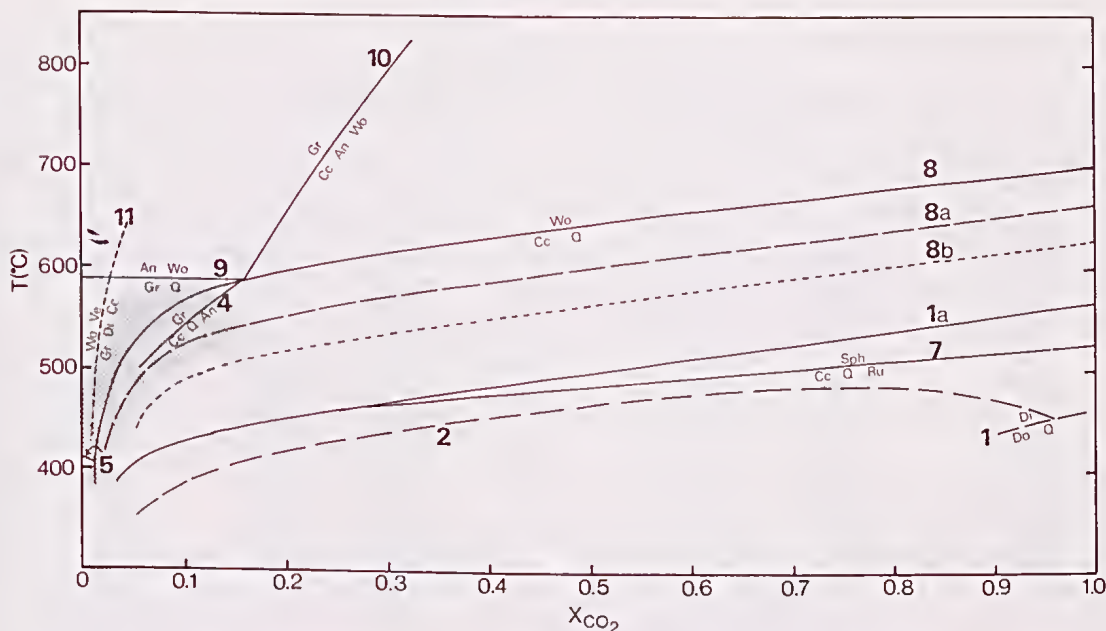
Fig. 12 — T-X_{CO_2} plot of the various equilibria controlling the mineralogy of the Blue Mount calc-silicate rocks. Reactions are numbered as they appear in the text. The section as shown is not isobaric. Equilibria 1a, 4, 5, 7, 8, 9 and 10 are at 2 Kb; equilibria 1, 2 and 8a at 1Kb and equilibria 11 and 8b at 0.5 Kb. Positions of the reactions 8 and 8a are from Jacobs and Kerrick (1981) and of 8b from Williams-Jones (1981). They are plotted to illustrate the marked effect of pressure on the calcite + quartz → wollastonite + CO_2 equilibrium. The shaded area represents the region in which the main phases crystallised.

11. 5 grossular + 4 diopside + 6 calcite + $4H_2O$ → 6 wollastonite + vesuvianite + 6 CO_2 (Williams-Jones 1981)

12. 2 grossular + 2 diopside + wollastonite + calcite + 2 H_2O → vesuvianite + 2 quartz + CO_2 (Ito & Arem 1970).

Equilibrium curves for most of these reactions are reasonably well known, either from thermodynamic calculations or experimental data. They are shown in the T-X_{CO_2} plot of Fig. 12. On this diagram, pressures for each equilibrium vary from 0.5 Kb (reaction 11), through 1 Kb (reactions 1 & 2) to 2 Kb (reactions 4, 7, 8, 9, 10). The invariant point formed by the intersection of reactions 4, 8, 9 and 10 and marked by the assemblage grossular + anorthite + wollastonite + calcite + quartz (+ CO_2) lies close to 600° C at 2 Kb. This assemblage is present on the scale of a thin section in many of the Blue Mount rocks and appears to represent conditions close to the peak of metamorphism. The marked effect of pressure on the topology of reaction 8, shown in Fig 12, suggests that the invariant point may be somewhat lower, around 550°C, for pressures as low as 0.5 Kb.

The stability relations of vesuvianite (idocrase) were investigated by Ito and Arem (1970), Shoji (1971) and Hochella et al. (1982). However, agreement between these studies is limited, due to the complexity of the substitutional chemistry of vesuvianite and the sensitivity of stability fields to varying starting compositions. The lower temperature stability limits of (Mg-rich) vesuvianite is significantly reduced by the presence of quartz,

to around 380° C at $P_{H_2O} = 1$ Kb, with respect to the assemblage grossular + diopside + wollastonite (Hochella et al. 1982). The upper stability limit, above which melilite and monticellite are reaction products, was determined to be around 700°C (Ito & Arem 1970) or 800° C (Hochella et al. 1982). The absence of these minerals at Blue Mount sets an upper temperature limit of 700°C. The prehnite decomposition equilibrium (reaction 6) has been determined to lie at 440°C at 1 Kb (Liou 1971). Thus the prehnite observed is most likely to represent retrograde crystallization. This conclusion is supported by the coexistence of prehnite and scolecite in one coarse grained patch.

SPHERULE-BEARING ROCKS: The assemblage in the spheroidal blebs (essentially grossular-wollastonite-diopside-sphene) indicates that reactions 4, 7 and 8 were instrumental in their formation. The contrasting mineralogy between spherules and matrix suggests that the former were originally calcite-quartz-calcic plagioclase-rutile inclusions in a more micaceous, i.e., K-rich, host. However, the spherulitic forms appear to represent nucleation and growth rather than merely isochemical reactions within inclusions.

CHEMISTRY OF THE BULK ROCKS

Three representative Blue Mount rock types and the coexisting pale and dark fractions from sample E10544 were analysed by conventional XRF and wet chemical (for Fe^{2+}) techniques. In addition, a fine-grained sample

TABLE 8
CHEMICAL ANALYSES OF CALC-SILICATE ROCKS FROM BLUE MOUNT (1-5) AND BONNIE DOON (6)
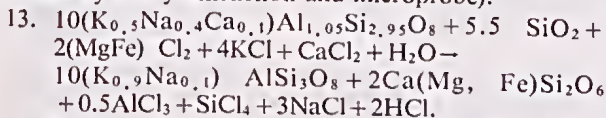
Wt%	1	2	3	4	5	6
SiO_2	65.12	59.12	51.12	46.04	48.82	49.45
TiO_2	0.24	0.67	0.57	0.48	0.58	0.44
Al_2O_3	14.30	11.59	11.99	10.95	12.76	8.95
Fe_2O_3	0.68	0.56	0.10	1.12	1.74	—
FeO	2.94	4.90	3.84	3.43	3.70	3.43
MnO	0.03	0.08	0.07	0.09	0.09	0.07
MgO	2.35	2.85	2.52	2.91	2.69	3.15
CaO	4.29	10.42	22.72	30.24	20.85	29.48
Na_2O	2.33	1.71	1.30	0.05	0.51	4.97
K_2O	4.35	5.47	2.44	0.07	4.50	0.94
P_2O_5	0.15	0.17	0.09	0.10	0.10	0.08
Ig. Loss	nd	nd	nd	4.01	nd	nd
Total	97.28	97.59	96.76	99.49	96.34	100.96
ppm						
V	99	82	85	75	100	62
Cr	120	106	113	219	249	121
Ba	1696	2464	970	31	3724	329
Sc	11	23	11	10	11	8
Cu	21	173	38	142	45	122
Co	10	15	18	19	16	16
Zr	273	352	235	149	208	167
Y	28	34	32	21	29	23
Zn	70	114	117	81	93	84
Ni	48	53	77	69	67	57
Sr	814	1960	2022	213	1492	781
Rb	209	301	136	12	206	58
Cl	127	195	242	128	184	172
S	2277	147	97	41	379	136
Pb	18	19	13	8	89	12
CIPW Norms						
Q	21.99	7.93	—	0.39	—	—
Or	25.71	32.33	14.42	0.41	18.10	—
Ab	19.72	14.47	9.24	0.42	—	—
Ne	—	—	0.95	—	2.34	22.10
Ns	—	—	—	—	—	0.29
Lc	—	—	—	—	6.66	4.36
An	15.71	7.79	19.67	29.45	19.24	—
Di	3.74	29.56	25.12	24.46	23.04	27.64
Hy	7.65	—	—	—	—	—
Wo	—	2.98	25.92	37.55	23.11	42.09
Mt	0.99	0.81	0.14	1.62	2.52	—
Ilm	1.41	1.27	1.08	0.91	1.10	0.84
Ap	0.37	0.48	0.21	0.24	0.24	0.19
Ratios						
An	58	19	28	32	29	—
Di	14	73	36	27	35	40
Hy	28	—	—	—	—	—
Wo	—	7	37	41	35	60

Samples: 1, Calc-silicate hornfels (dark fraction) (NMV E10544) Blue Mt.; 2, Calc-silicate hornfels (pale fraction) (NMV E10544) Blue Mt.; 3, Calc-silicate hornfels (NMV E10280) Blue Mt.; 4, Calc-silicate hornfels (NMV E10283) Blue Mt.; 5, Calc-silicate hornfels (spotted) (NMV E10713) Blue Mt.; 6, Calc-silicate hornfels Bonnie Doon.
nd: not determined.

of calc-silicate hornfels from the Bonnie Doon location (Phillips & Wall 1980) was analysed. This specimen consisted mainly of wollastonite, diopside and K feldspar with small lenses of calcite, wollastonite and quartz. Major and trace element data are shown in Table 8.

The bulk rocks have variable composition, chiefly involving Ca and Si, and to a lesser extent K. Of the trace elements, Ba, Sr and S show the greatest variation. It is reasonable to assume that much of the chemical variation reflects differences in original sedimentary components, particularly in terms of the illite (clay-mica) (i.e. K), calcium carbonate (Ca) and quartz (Si) fractions. However, analyses of the dark and pale portions of sample E10544 indicate that alteration of the original dark hornfels resulted in the removal of Si, Al, Na and S and the concentration of Ca, K, Fe, Mg, Ba, Sr and Cl in the pale alteration zones. If this analysis pair is representative, then the metamorphism was not isochemical, at least in its final stages, but was accompanied by exchange of components from fluids in which Ca, Si, Na, S, Al and K were the most mobile elements. Thus any original compositional differences between individual rock types have been overprinted during metamorphism. The amount of chemical modification is difficult to quantify in the absence of clear zonation in assemblages. However, it is possible to derive a hypothetical reaction for the alteration of sample E10544 (neglecting oxidation of sulphides), based on the bulk rock compositions, the relative abundances of major minerals (Table 7), the average alkali feldspar composition in the dark fraction ($K_{0.5}Na_{0.4}Ca_{0.1}Al_{1.05}Si_{2.95}O_8$—obtained by microprobe) and the average K-feldspar in the pale fraction ($K_{0.9}Na_{0.1}AlSi_3O_8$—obtained by X-ray diffraction and microprobe):

13. $10(K_{0.5}Na_{0.4}Ca_{0.1})Al_{1.05}Si_{2.95}O_8 + 5.5 \ SiO_2 + 2(MgFe) \ Cl_2 + 4KCl + CaCl_2 + H_2O \rightarrow 10(K_{0.9}Na_{0.1}) \ AlSi_3O_8 + 2Ca(Mg, \ Fe)Si_2O_6 + 0.5AlCl_3 + SiCl_4 + 3NaCl + 2HCl.$

This overall reaction does not quite balance, in that, as shown, it produces an extra 0.5 mole Cl⁻, but this can be accounted for by the simplification of the feldspar compositions. The reaction results in the consumption of quartz and the production of diopside, in agreement with observed mineralogical changes during alteration (Table 7). All mobile cations (K, Ca, Mg, Fe, Si, Al, Na, H) are assumed to be present as chlorides, which is a further simplification, although chloride would have been a major component in the solutions (Vidale & Hewitt 1973). Note that the use of this equation implies that factors such as pH and the activities of silica, Ca^{2+} and Mg^{2+} may be of significance. A similar reaction could possibly be written involving plagioclase feldspars if compositions of reactants and products were known. Reaction 13 cannot account for the magnitude of the changes in bulk rock composition as alteration proceeded. However, if Al, Si and Na were removed in solution, and K and Ca added, the changes would be in the observed direction. The composition of each rock type in the (silica-saturated) Al_2SiO_5—(Mg, Fe)SiO_3—$CaSiO_3$ system is plotted in Fig. 13. The mineralogy

predicted from the plotted positions agrees well with that observed.

The widespread occurrence of grossular in the Blue Mount rocks, and its absence from the Bonnie Doon calc-silicates (where the equivalent assemblage plagioclase + wollastonite + calcite occurs — Phillips & Wall 1980) may arise from different Na contents in the bulk rocks. The progressive addition of albite to plagioclase solid solution results in a significant shift of the equilibrium (represented by reaction 10) with grossular formation being favoured by lower Na contents (Kerrick 1974).

CONDITIONS OF METAMORPHISM
Pressure and Temperature

There are no independent mineralogically-based means available to determine the pressure at which the Blue Mount rocks formed. However, some conclusions may be drawn from geological relationships. The granodiorite has intruded the main bounding fault of the Acheron cauldron complex, and hence largely postdates subsidence along the fault. From the nature of the emplacement mechanism of the volcanics, i.e. the filling of a collapse structure, it may reasonably be assumed that the levels of the top of the volcanic pile and the surrounding land surface outside the boundary fault were roughly concordant at the time of intrusion. The present altitude difference between the highest points on the eroded volcanic pile and Blue Mount is about 400 metres. Thus, if no more than 100 metres have been eroded from the vertical thickness of the volcanics, then the contact metamorphism could represent intrusion to depths as shallow as 500 metres. Even allowing for greater erosion rates, there is little doubt that the Blue Mount rocks crystallized at pressures of the order of 0.5 Kb or less. A similar conclusion was reached for the Bonnie Doon calc-silicate rocks (Phillips & Wall 1980).

Estimates of temperature may only be loosely based on the experimentally determined equilibria matching the natural assemblages (Fig. 12). The best reaction to constrain temperature is grossular + quartz → 2 wollastonite + anorthite (9) since it is fluid-absent. Given that the calcic feldspar in the rocks is not pure anorthite, the estimated temperature from this equilibrium is a maximum. A maximum temperature of between 500° and 550°C is suggested for the Blue Mount rocks, in general agreement with estimates for the Bonnie Doon occurrence (Phillips & Wall 1980). Temperatures of around 400°C for equilibration in the retrogressive stages are suggested by the presence of vesuvianite, prehnite and scolecite.

Solution Chemistry

Binary solutions consisting of H_2O and CO_2 are the main agents involved in formation of calc-silicate assemblages under a wide range of conditions (Kerrick 1974, Rice & Ferry 1982). These solutions may be derived by either devolatilization reactions within the rocks during prograde metamorphism, or by infiltration of
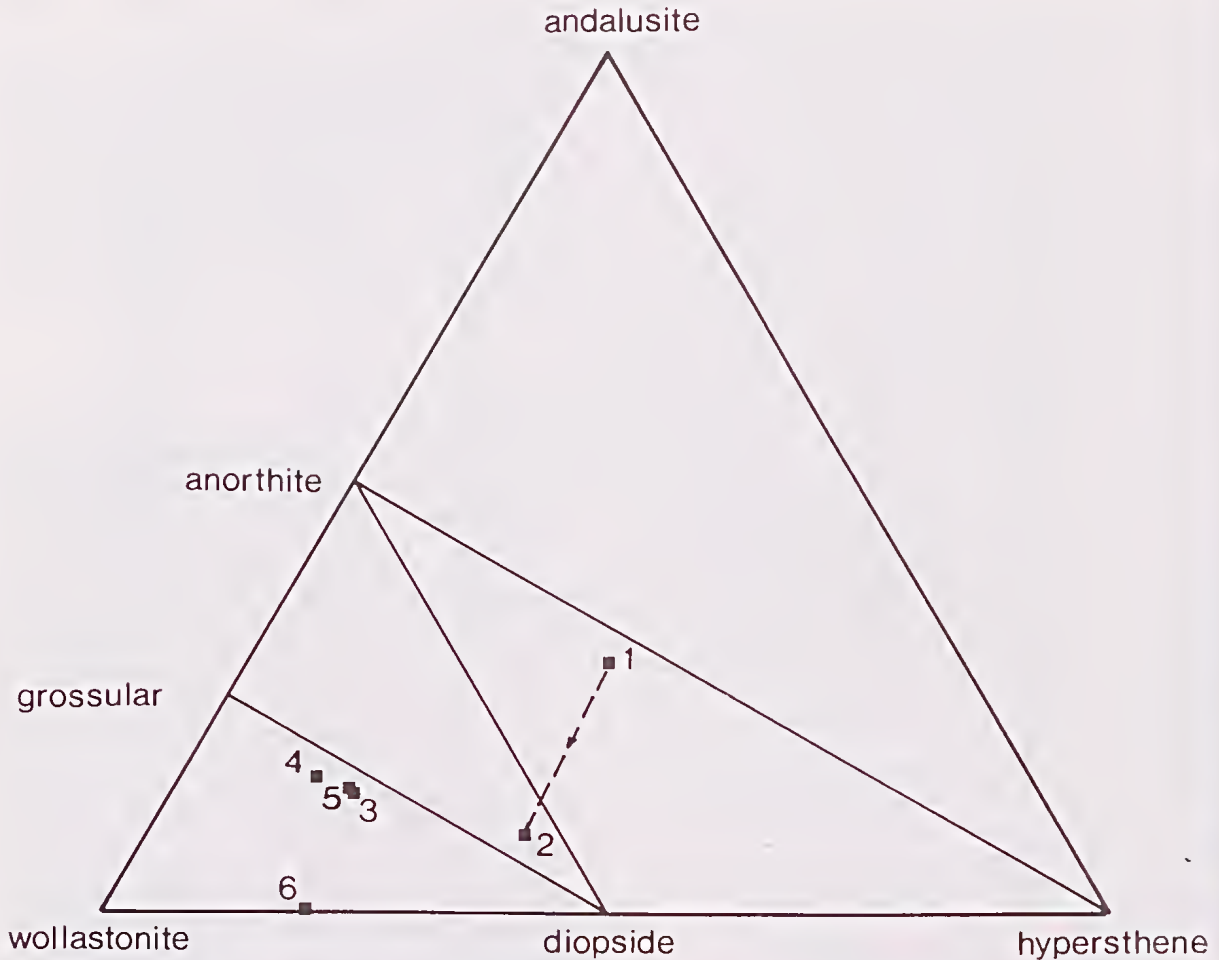
Fig. 13 — Bulk compositions of the Blue Mount and Bonnie Doon calc-silicate rocks plotted in terms of normative components. The arrowed tie-line joins the dark and pale hornfels in sample E10544.

solutions from external sources, such as late-stage magmatic or meteoric fluids (Rumble *et al*. 1982). At Blue Mount, the main reactions (Fig. 12) occurring close to the peak of prograde metamorphism and responsible for the alteration of the dark hornfels are consistent with equilibration in the presence of solutions with X_{CO_2} less than 0.2. In some cases, particularly during crystallization of vesuvianite and prehnite during retrogression, extremely water-rich fluids ($X_{CO_2} < 0.05$) are indicated (Hochella *et al*. 1982, Williams-Jones 1981). Nearly all the devolatilization reactions occurring during progressive metamorphism of the Blue Mount rocks produced CO_2. In order to maintain low X_{CO_2}, the CO_2 produced must have been diluted by a large reservoir of water-rich fluid, derived from either the intrusion, from the wet sediments themselves or from a meteoric source and transported along grain boundaries or on fracture systems. It is unlikely that the mixing process resulted in a totally homogenous fluid phase. The existence of coarse-grained patches, veinlets, clots, and remnant alteration textures in fine-grained rocks suggest variable infiltration rates and hence variable fluid compositions. As an extreme example, the presence of both diopside-quartz and grossular-wollastonite veinlets, although not in the same rock type, represent the localized effects of CO_2-rich and H_2O-rich solutions respectively. Phillips and Wall (1971) predicted variability of CO_2 activity on the scale of a handspecimen at Bonnie Doon, based on fluctuations in the proportions of coexisting wollastonite, calcite and quartz. Such an effect is likely in the Blue Mount rocks. In such a small-scale, unzoned deposit, across which P-T gradients may be undetectable, it is difficult to determine any mineralogical evidence for change in solution composition with time. However, it is likely that solutions became increasingly water-rich, resulting in localized crystallization of vesuvianite, prehnite and scolecite during retrogression.

The fluids responsible for the alteration of the dark hornfels were able to move significant amounts of Si, Al, Ca, Na, K, Cl and S through the Blue Mount rocks. These elements are likely to be amongst the most com-

mon and mobile in metamorphic fluids (Vidale & Hewitt 1973, Crawford *et al.* 1979, Ferry & Burt 1982, Ferry 1983). As well as cations, or cationic complexes, metamorphic fluids commonly contain significant H_2S, CH_4 (Ferry & Burt 1982), chlorides (Sisson *et al.* 1982, Crawford *et al.* 1979) and fluorides. Although the overall effect of up to 10 wt% NaCl on CO_2 activity in H_2O-CO_2 fluids may not be of significance at low pressures (Jacobs & Kerrick 1981), localized concentrations may influence the stable assemblage. For example, scapolite crystallization may occur in the presence of NaCl-rich fluids. Although fluorides are of lesser significance in metamorphic solutions, being strongly partitioned into crystallizing silicates, it is possible that localized F concentrations may favour formation of vesuvianite rather than grossular.

Apart from their ability to change the bulk chemistry of the rocks, the solutions influenced the structural state of the K feldspars. The slightly lower degree of order in the K feldspars from the pale altered zones compared to the dark hornfels suggests a higher crystallization temperature. However, it is unlikely that a significant temperature gradient could be maintained over such relatively short distances. As the continued presence of metamorphic solutions in the alteration zones would facilitate the K feldspar ordering process during cooling, the observed difference is the opposite to what might be expected. The explanation may lie in recrystallization during alteration which effectively removed pore fluids from the altered zones, so that the feldspar ordering process was not assisted. Alternatively compositional differences, particularly the higher levels of Ba in the altered zone K feldspars (small amounts of Ba may hinder ordering—Makagon & Schmakin 1971) may be sufficient to account for the structural state differences.

DISCUSSION AND CONCLUSIONS

Taylor and O'Neill (1977) defined skarn as referring to coarse-grained rocks which are the products of metasomatism, whereas calc-silicate hornfels best described rocks which are the result of isochemical metamorphism. This simple distinction has subsequently been recognised as inadequate to cover the diversity of skarn and skarn-like deposits (Einardi & Burt 1982). The contact metamorphism of the Blue Mount rocks was clearly not isochemical, at least on the scale of individual beds. The original sediments were a limited sequence of argillaceous limestones and calcareous mudstones. Metamorphism appears to have proceeded in two stages, particularly in the less reactive rock types represented by the dark hornfels. An early, largely isochemical (apart from devolatilization) recrystallization was followed by a later metasomatic alteration, the effects of which can only be monitored where the rocks were partially altered. In contrast to the dark hornfels, the massive pale hornfelsic and mottled rock types show no evidence for a multi-stage process. Local exchange of components between beds and partial homogenization, with the formation of 'skarnoids', have now been

recognised in interlayered sequences such as that on Blue Mount (Einardi & Burt 1982, Harris & Einardi 1982).

The fluids responsible for the metasomatism were either internally-derived from the presumably originally wet sediments themselves (i.e. they were a product of both pore fluids and devolatilization reactions) or else were of meteoric origin. Although the low-pressure, high-level environment may appear to favour the influx of magmatic fluids, the iron-rich assemblages characteristic of magmatic metasomatism are lacking in the carbonate rocks. Some magmatic influence cannot be ruled out entirely however, particularly if the overall system (intrusion plus sediments) was relatively depleted in iron.

The bulk chemistry of the rocks was variable, but within sufficiently narrow limits to enable the crystallization of grossular in most rock types. The overall low Na content was probably the critical factor influencing grossular crystallization.

Based on experimental and calculated data for relevant phase equilibria, the estimates for P-T conditions during metamorphism of the Blue Mount rocks ($P \leq 0.5$ Kb, $T_{max} = 500$-$550°C$) are in general agreement with those deduced for the only other stratigraphically similar occurrence in the region (Bonnie Doon). The major assemblages equilibrated in the presence of water-rich fluids ($X_{CO_2} < 0.2$).

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